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Ventilator Graphics

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VENTILATOR GRAPHICS

INTRODUCTION

As anaesthetists we are often referred to as the ventilation experts, and rightly so as we ventilate patients daily in both theatre and ICU. However, we require significant understanding into how ventilators work as well as an understanding of ventilator-patient interactions. Ventilator technology has greatly improved recently and ventilator graphics are an added tool to provide more insights into the patient-ventilator interaction. Yet these graphics are not always interpreted adequately to optimise ventilation.

Ventilation is a high resource consuming intervention in critical care. Ventilated patients are also at high risk of ventilator related complications. These patients require constant monitoring and care. By assessing ventilator graphics at the bedside, clinicians are able to decrease complications by optimising ventilation-patient interaction and diminishing ventilator dys-synchrony.

RESPIRATORY PHYSIOLOGY

In order to understand ventilation, an understanding of respiratory physiology is required. A simplified system of the complex respiratory system is the single-alveolar compartment model of the respiratory system. This is an easier to understand format that allows clinicians to measure the 3 most common ventilator parameters and use them in the understanding of the respiratory system. The respiratory properties of interest are resistance and elastance.

Resistance is the ratio of pressure change to flow change. Elastance is the ratio of pressure change to volume change [1].

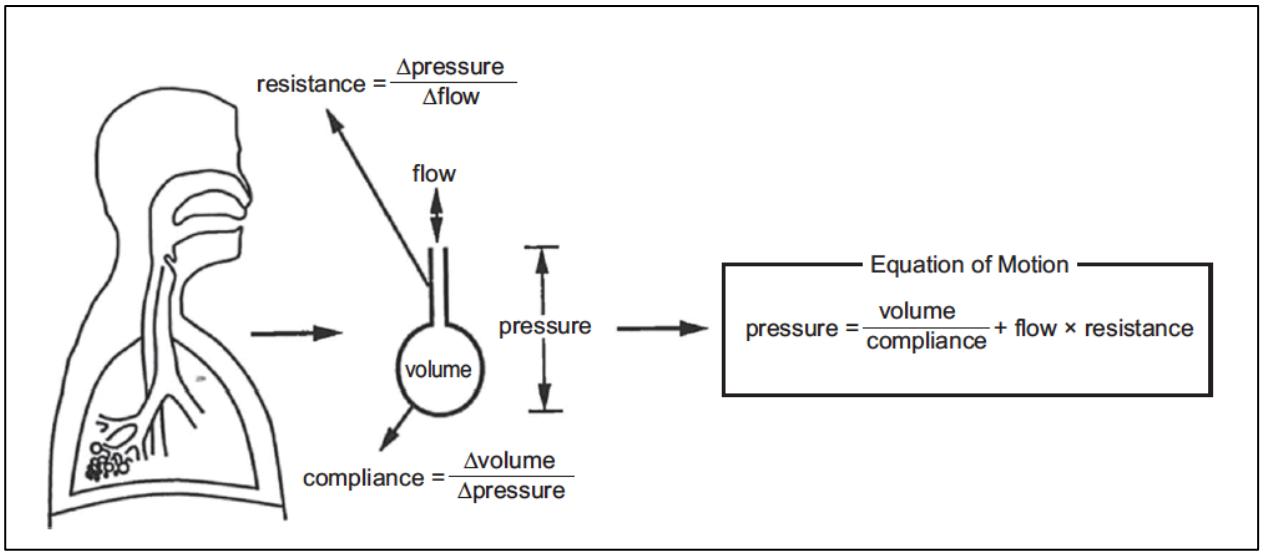

Figure 1: Single-alveolar compartment model of the respiratory system [1]

The single compartment model of the respiratory system can be described in a graphical form or mathematical form. Figure 1 above demonstrates the graphical form [1]. The diagram illustrates all factors that must be overcome in order to translate the energy used to contract the diaphragm into the volume of air inspired.

The mathematical equation for respiratory mechanics is known as the "equation of motion". It describes the single compartment model in terms of pressure, volume and flow as functions of time.

$$P_{vent} = (E \times V) + (R \times V')$$

Or

$$P_{vent} = (V / C) + (R \times V')$$

E = respiratory system elastance

V = volume over time

R = airway resistance

V ' = flow over time

C = respiratory system compliance

Newtons third law of motion applied to respiratory mechanics states that: the pressure that the ventilator exerts is opposed by an equal and opposite pressure exerted by the patient.
The right side of the equation shows that the pressure exerted by the patient is made up of 2 main components: elastance and airway resistance.

Elastance is the reciprocal of compliance and is the ratio of the change in pressure to change in volume (P / V) or, the pressure that is required to inflate the lungs. This pressure is used to inflate both the lungs and the chest wall [1].

Pressure control modes of ventilation

$$\boxed{P_{vent}} = (E \times V) + (R \times V')$$

By using this equation it can assist in understanding ventilation mechanics. In pressure control ventilation, the pressure that must be generated is set by the operator and is reflected on the left side of the equation (i.e. P_{vent}). Since pressure is the control variable, tidal volume delivered must be monitored. The resultant tidal volume that is actually achieved is a result of the right side variables, i.e. the total elastance (lung and chest wall), the airway resistance and the air flow characteristics [1].

Volume control modes of ventilation

$$P_{vent} = \boxed{E \times V + R \times V'}$$

Volume control modes control the right side of the equation, by setting the tidal volume (V) and inspiratory flow waveforms (V'). Since volume is controlled, pressure must be monitored. Therefore changes in the patients elastance or airway resistance will be noted in the left side of the equation, i.e. changes in the peak inspiratory pressure [1].

Patient spontaneous respiratory efforts

$$P_{vent} + P_{mus} = E \times V + R \times V'$$

Spontaneous respiratory efforts also needs to be taken into account. Patients' respiratory muscles and diaphragm generate a pressure during a respiratory effort and this is added to the left side of the equation. When patients generate a pressure with their spontaneous effort this leads to changes in the pressure, volume or flow [1].

ROLE OF MONITORING VENTILATOR WAVEFORMS

Monitoring ventilator waveforms provides added information to the clinician managing the patient. Interpretation of ventilator waveforms can allow for the detection of respiratory abnormalities before they become clinically evident. They also allow for the detection of patho-physiological processes and assist in distinguishing between different processes. Quicker identification of pathological processes will lead to quicker management of problems and this may translated into shorter ventilation times.

The role of monitoring waveforms [2]:

- Identify pathological processes
- Recognize a change in the patient's condition
- Optimize ventilator settings and treatment
- Determine the effectiveness of ventilator settings and treatment
- Detect adverse effects of mechanical ventilation
- Minimize the risk of ventilator-induced complications

SCALARS

Scalars are graphical representations of specific respiratory parameters depicted over time. The three scalars that are displayed on most ventilators are Pressure, Volume and Flow. These are plotted on the y-axis with time on the x-axis. Each scalar depicts the entire breath, or multiple breaths depending on the respiratory rate, for both inspiratory and expiratory phases. These scalars allow clinicians: to assess the variable of interest over time, detect ventilatory problems, assess response to an intervention and adjust treatment accordingly [1].

(i) Volume vs Time Scalar

This is the graphical representation of the amount of gas delivered to the lungs by the ventilator over time. It is a calculated value by mathematical integration of the area under the flow-time curve. It provides a visual representation of the tidal volume, inspiratory time for both inspiratory and expiratory phases. As the inspiratory and expiratory volumes should be equal, this scalar is able to provide information about air leaks if the values are not similar. This is seen when the expiratory curve decreases as usual but does not reach baseline and instead plateaus before the subsequent inspiratory part of the next inspiratory cycle occurs, i.e. there is a missing volume [3]. The volume of the leak can be determined by measuring the distance from the plateau to the baseline.

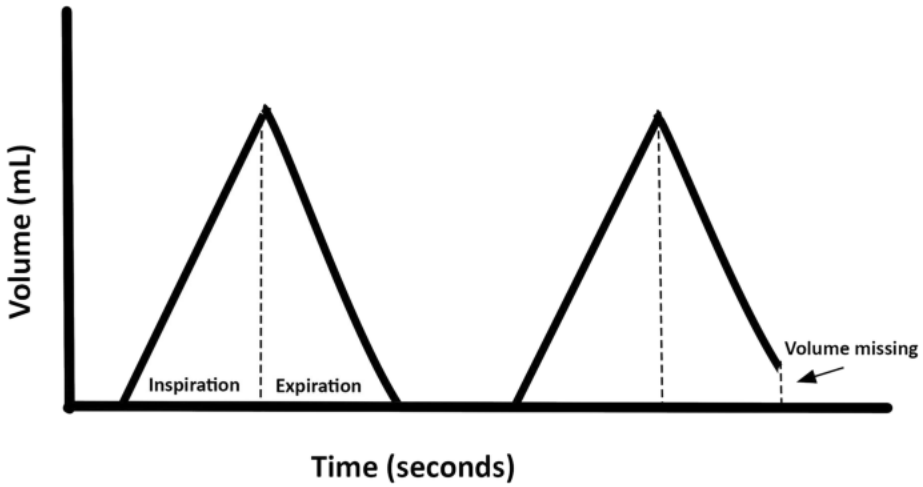

Figure 2: Volume-time scalar. The first waveform shows equal inspiratory and expiratory volumes. The second waveform shows a small expired volume signifying a leak [3].

(ii) Flow vs Time Scalar

The flow of gas between the patient and the ventilator is depicted in this scalar. It is a directly measured value as measured by a flow sensor. Flow sensors used in adult ventilators are of 2 main types: variable-orifice flow sensor (e.g. Hamilton ventilators) and the hotwire anemometer flow sensor (e.g. Drager ventilators).

Inspiratory flow is positive and is usually represented above the baseline. Expiratory flow is depicted as negative flow below the baseline. The area under the curve represents the volume of air that is moved. The shape of the inspiratory curve is dependent on the mode of ventilation. With volume controlled modes, the flow rate is constant and this is depicted as a square scalar during the inspiratory phase. Pressure controlled modes have a downward slopping line (decelerating curve) as initially there is a high flow rate but it then tapers off as the lung fills with air [3].

This scalar is useful in providing further information regarding respiratory mechanics. The expiratory limb of this scalar changes when there is increased airway resistance to airflow. With obstruction to airflow and increased airway resistance, there will be a decreased peak expiratory flow and a prolonged time taken for the expiratory curve to return to baseline. This is a graphic representation of the process of increased airway resistance limiting the speed at which the lung empties and the volume that is emptied [3].

Air trapping is visible on this scalar and is also referred to as auto-PEEP or intrinsic PEEP ($PEEP_i$). This is depicted as the expiratory curve not returning to baseline of zero prior to the next inspiration occurring. Expiration is prolonged in patients with obstructive processes and therefore not completed before the next breath starts. This leads to breath stacking and trapping of air [3]. Other common abnormalities such as accumulation of secretions and bronchospasm are also detected on this scalar by the expiratory curve not returning to baseline and a decreased peak expiratory flow [1]. By performing an expiratory hold the intrinsic PEEP can also be determined using this scalar [3].

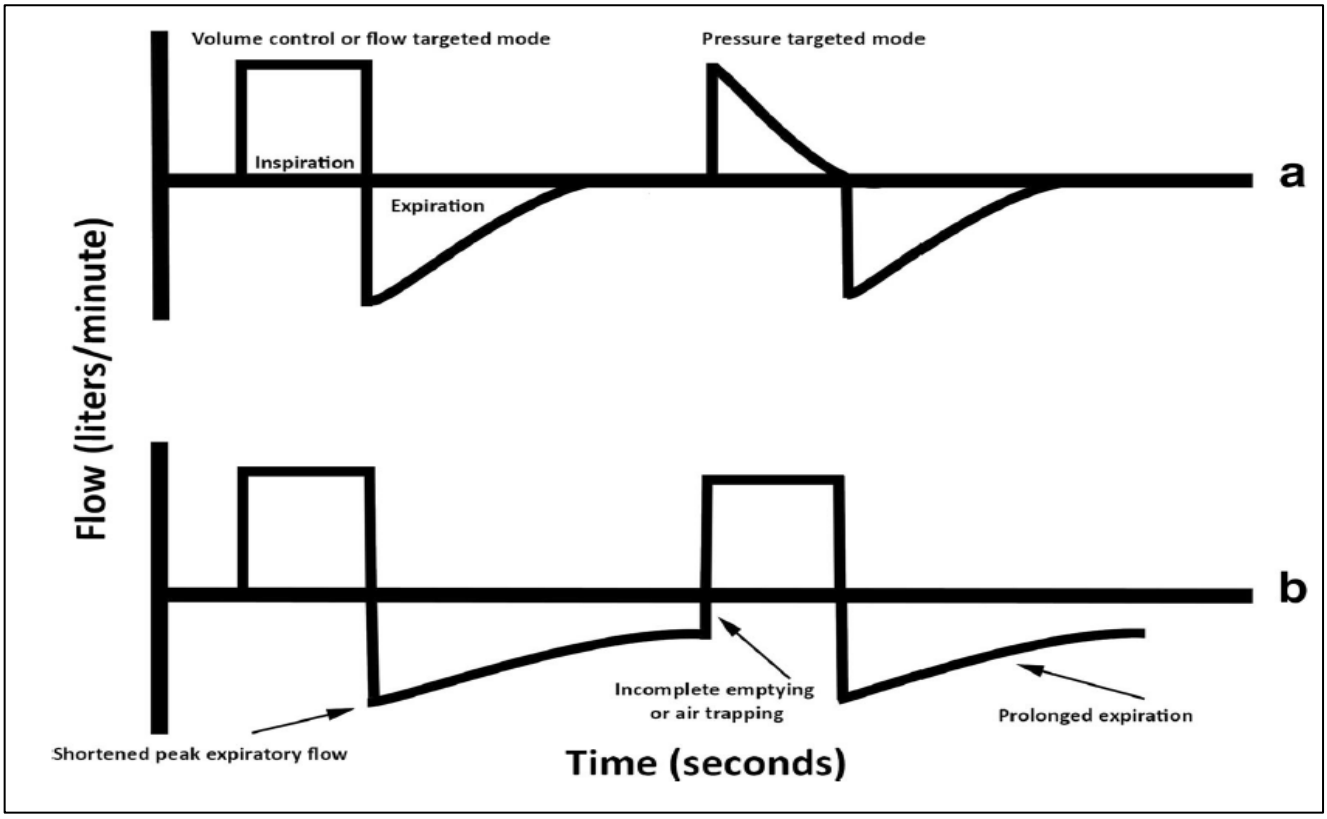

Figure 3: Flow versus time scalar. (a) The first waveform is square in shape and represents volume controlled ventilation, the second is a decelerating pattern and represents pressure controlled ventilation. (b) Volume controlled ventilation demonstrating that the expiratory flow does not return to baseline, known as air trapping, auto-PEEP or intrinsic PEEP [3].

(iii) Pressure vs Time Scalar

This is one of the most valuable scalars depicted on the ventilator and provides information on both dynamic and static lung mechanics [1]. Depending on the mode of ventilation this scalar is either fixed or variable. With pressure controlled modes, the delivered pressure is constant and therefore the scalar is a fixed square graphic (constant pressure). With volume controlled modes, the pressure increases as the lung fills during constant flow. The highest pressure at the end of the inspiratory curve is the peak inspiratory pressure and the baseline pressure indicates the PEEP.

By setting an inspiratory pause time, plateau pressure is displayed. Plateau pressure is the pressure in the airway when there is no airflow. It can only be measured during volume controlled modes as a constant flow is used therefore there is a larger difference between peak inspiratory and plateau pressures during the pause. Plateau pressure is an indication of the alveolar pressures and relates to lung compliance. Airway resistance is eliminated during an inspiratory pause as there is no gas flow and therefore plateau pressure does not inform on airway resistance [3].

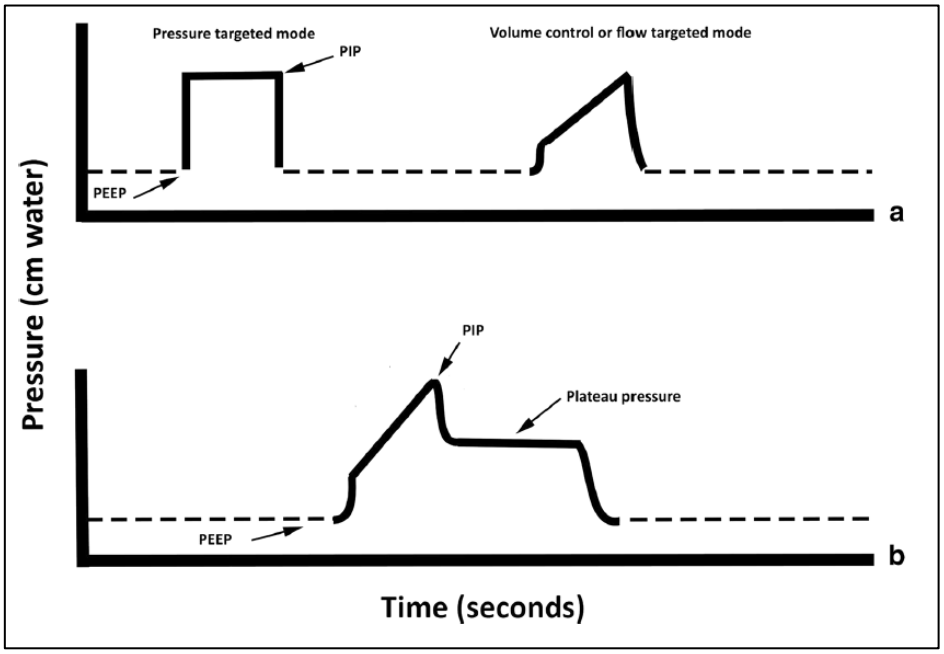

Figure 4: Pressure versus time scalar. (a) The first breath is a pressure controlled breath followed by a volume controlled breath. (b) a graphical depiction of peak and plateau pressures [3].

During volume controlled ventilation, trans-airway pressure is the difference between peak inspiratory pressure and plateau pressure, and this reflects airway resistance. If there is an increase in trans-airway pressure then there is an increase in airway resistance. If both plateau pressures and peak inspiratory pressures increase then this corresponds to an decrease in lung compliance [1].

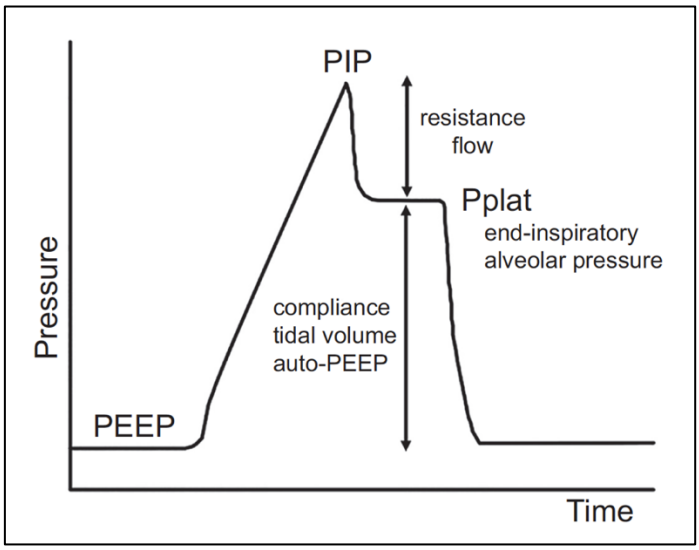

Figure 5: Pressure-time scalar displaying increase trans-airway pressure [1].

Driving pressure is also indicated on this scalar, as it is the pressure difference between plateau pressure and PEEP. Driving pressure is composed of two pressures, the transpulmonary pressure which is applied to the lungs and a pressure that is applied to the chest wall.

The plateau pressure must be measured in static conditions, when there is zero flow as this allows equilibration between the airway and alveolar pressures. An inspiratory hold of at least 3-seconds allows for the greatest accuracy in measuring plateau pressure [4].

Driving pressures can be monitored in both theatre and ICU to provide an indication of total lung strain as they have been found to have detrimental effects on lung protective strategies even if the plateau pressures and tidal volumes fall within lung protective ranges. Driving pressure can be used as a surrogate for transpulmonary pressure and indicative of lung strain, but as already mentioned it comprises of transpulmonary pressure and the pressure required to overcome the chest wall. So this can only be used as a surrogate when chest wall compliance is normal. Clinicians need to be aware of this caveat when chest wall compliance is abnormal or variable as in situations where there is increased abdominal pressures or increased pleural pressures. In these cases driving pressure diverges from transpulmonary pressures [4].

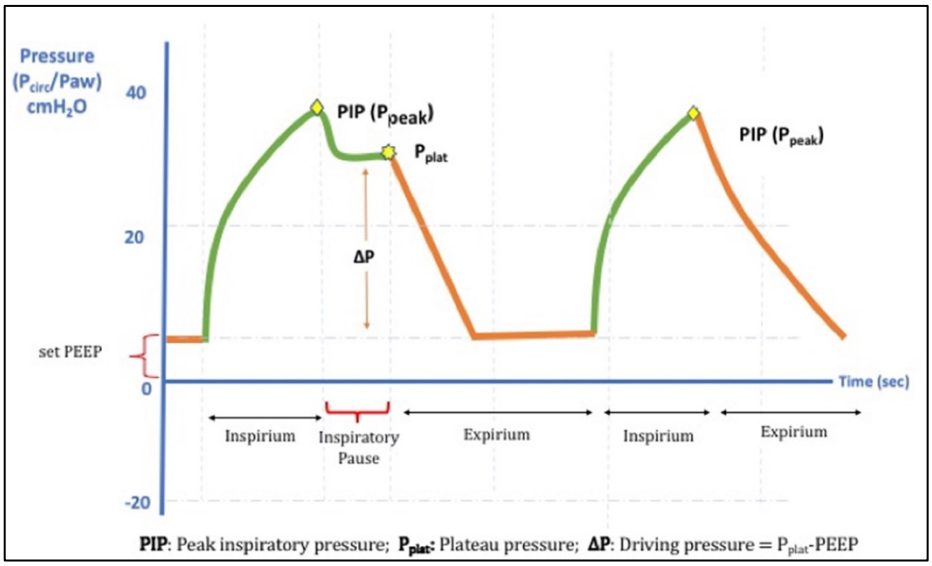

Figure 6: Pressure-time scalar showing the driving pressure (delta P) between the plateau pressure and PEEP [5].

Stress Index

This measurement is calculated from the pressure vs time scalar during volume controlled ventilation and is based on the theory that in normally compliant lungs the pressure increases at a constant rate with a constant rise in volume. This correlates to a pressure curve that has a straight slope or a stress index of 1 indicating no change in compliance during ventilation. If the slope has a upward or domed curve (convexed) the stress index is less than 1. This indicates that with increasing volume there is improvement in the compliance of the lung and recruitment occurs during tidal ventilation.

A stress index of more than 1 has an downward or scooped out curved slope (concaved) and this indicates that the lung becomes overdistended with higher volumes and has decreased compliance [1, 3].

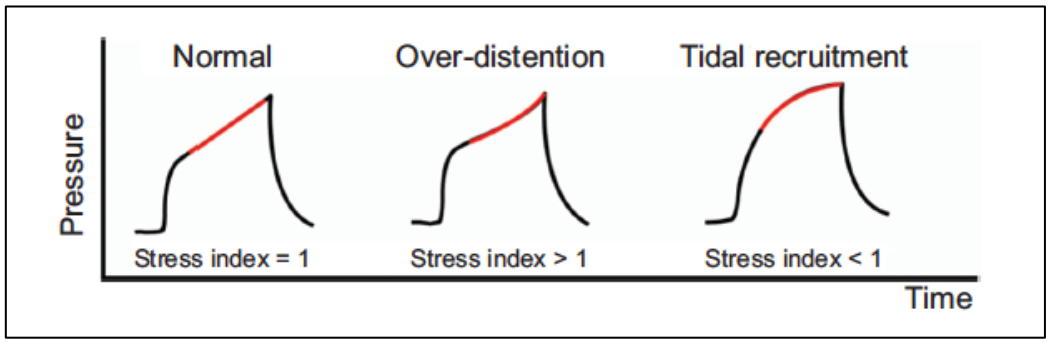

Figure 7: Pressure-Time scalar showing the stress index [1].

Trouble-shooting changes in scalars

(i) Changes in Compliance

Compliance is the ratio of change in volume over change in pressure. During volume controlled ventilation, the pressure time scalar is used to determine changes in compliance.

Decreased dynamic compliance is related to changes in airway resistance such as bronchospasm or a partial obstruction e.g. kinking of the endotracheal tube or circuit.

The formula for dynamic compliance is: $\mathbf{C_{dynamic} = V_{tidal} / (PIP - PEEP)}$

This scalar will demonstrate an increase in Peak inspiratory pressure as well as an increase in the difference between peak inspiratory pressure and plateau pressure. Plateau pressure remains constant with increases in airway resistance[6, 7].

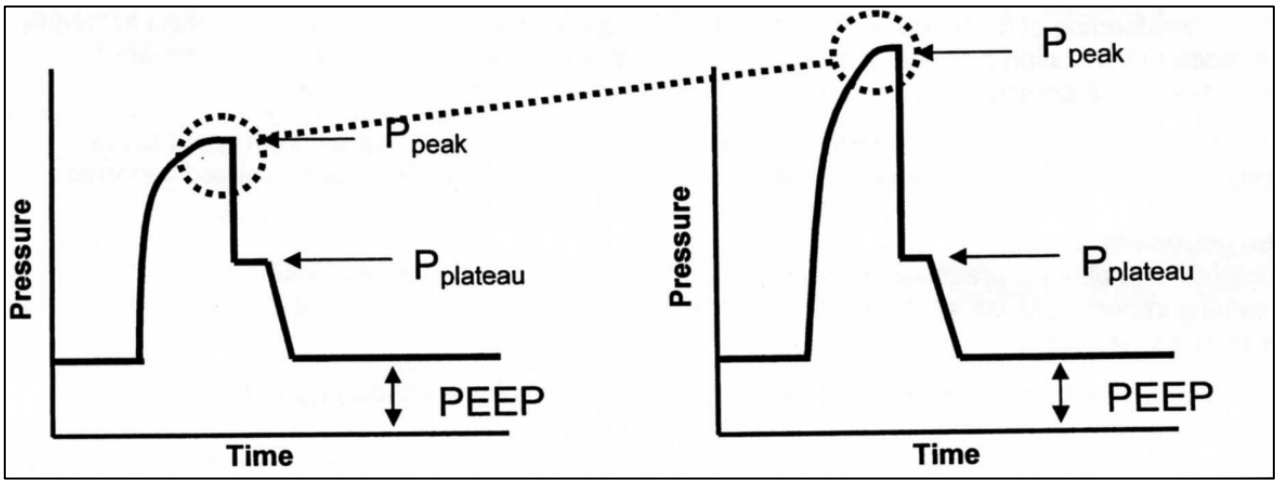

Figure 8: Pressure-time scalar showing the change in dynamic compliance during volume controlled ventilation [6].

Static compliance is related to changes in lung compliance and is due to lung associated pathology such as ARDS or pneumonia. This will result in an increase in plateau pressure and the relationship between peak and plateau inspiratory pressures remain constant. Since the lung is 'stiffer' there will be a knock-on effect of increased airway resistance, so peak pressures increase as well. Therefore, changes in static compliance will always affect dynamic compliance but the inverse is not always true as dynamic compliance changes (airflow resistance) can occur independently of static compliance.

The formula for static compliance is: $\mathbf{C_{static} = V_{tidal} / (P_{Plateau} - PEEP)}$

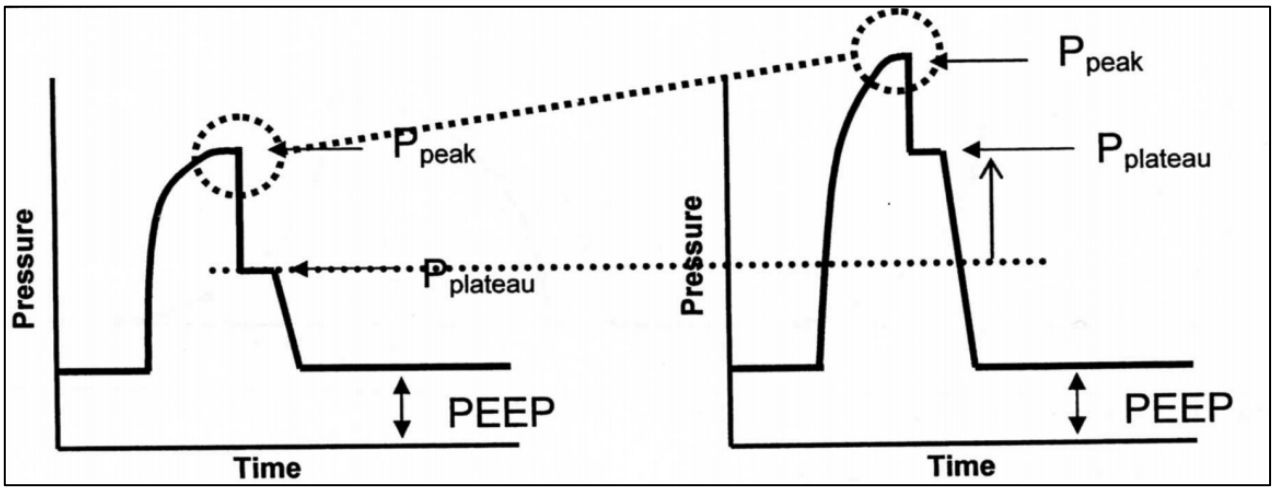

Figure 9: Pressure-time scalar showing the change in static compliance during volume controlled ventilation[6].

During pressure controlled modes changes in compliance are seen on the flow time scalar as a decreased area under the curve. The pressure time scalar remains constant[6, 7].

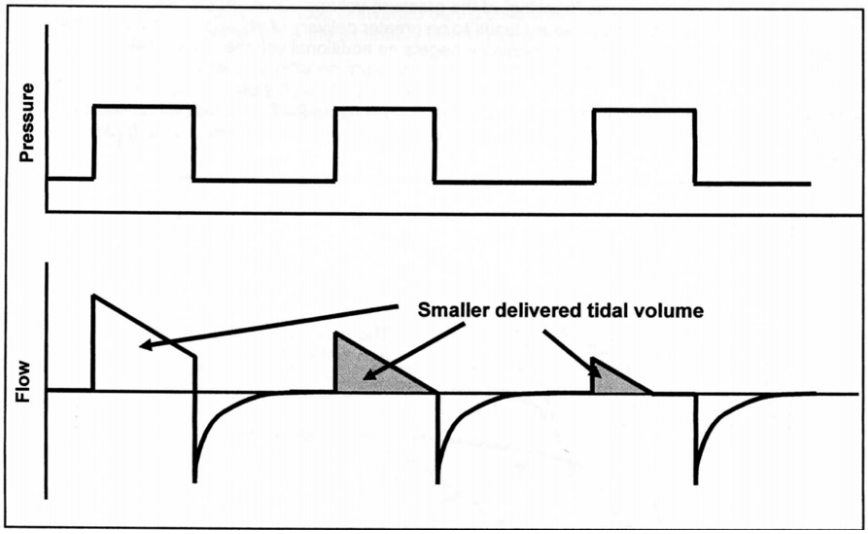

Figure 10: Pressure-time scalar showing decreasing compliance with 3 successive breaths [8].

(ii) Air trapping and intrinsic PEEP

As previously mentioned, in the flow-time scalar it is possible to determine if there is air-trapping. The expiratory curve does not return to baseline prior to the next breath initiation. This is demonstrated above.

Intrinsic PEEP ($PEEP_i$)
Using the pressure time scalar, intrinsic PEEP can be measured using an expiratory hold. During an expiratory hold, there is no air flow. The expiratory valve of the ventilator is held open and the airway pressure (measured by the ventilator) can equilibrate with the alveolar pressure. This allows for the measurement of intrinsic PEEP as long as intrinsic PEEP is greater than the set extrinsic PEEP.

Measuring $PEEP_i$ or auto-PEEP will assist the clinician in determining the threshold to set the trigger for the patient to trigger the ventilator. The pressure that the patient will have to generate in order to overcome the auto-PEEP and then meet the required trigger value can be significantly higher than expected [8].

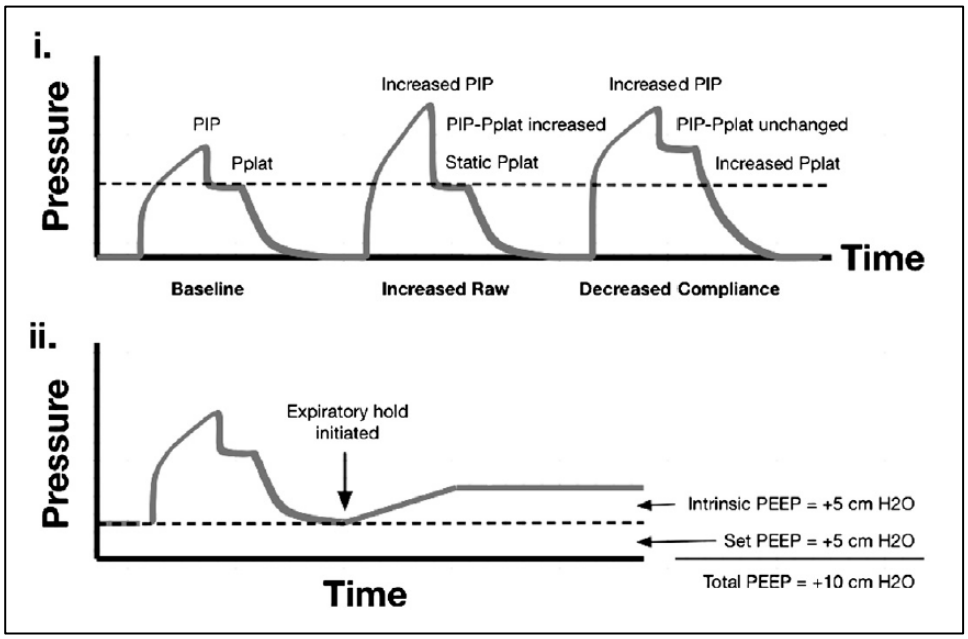

Figure 11: Pressure-time scalar showing an expiratory hold [8].

(iii) Optimising inspiratory time

Using the flow time scalar inspiratory time can be optimised. Using a constant pressure mode, the flow time scalar is a decelerating flow pattern. In the diagram below it is clear how inspiratory time can be optimised. “b” indicates an inspiratory time that is too short and the flow does not return to baseline prior to exhalation starting. “c” demonstrates optimal inspiratory time with the flow returning to baseline prior to exhalation. “d” demonstrated an inspiratory time that is too prolonged with there being a period of no flow prior to exhalation starting [8].

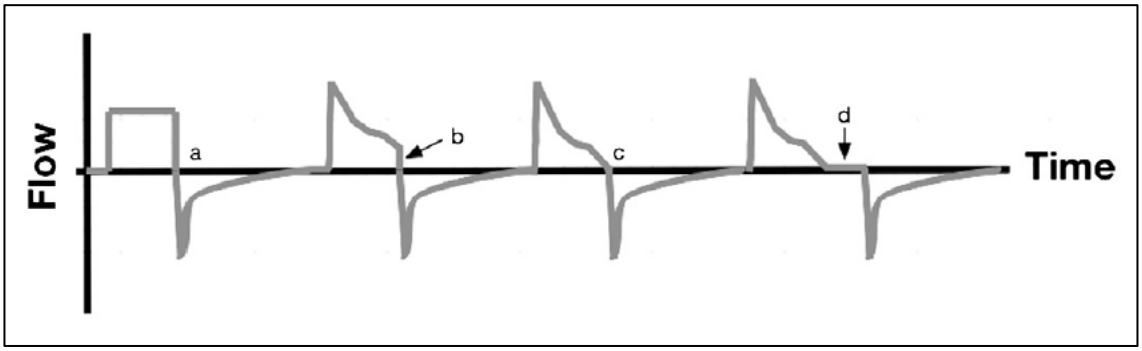

Figure 12: Examples of how changes in inspiratory time affect the flow pattern as explained in text above [8]

LOOPS

These graphics illustrate two variables plotted against each other, giving a 2-dimensional view of respiratory mechanics. The loops each plot a variable, either pressure or flow on the x- axis with volume on the y-axis. Each loop has both an inspiratory and expiratory limb.

i)Pressure-Volume Curve

This curve displays pressure on the x-axis and volume on the y-axis. The inspiratory limb starts at the lower left corner and progresses in a counter-clockwise direction. If PEEP is applied, then the curve starts at the pressure level corresponding to the set PEEP on the x-axis. The inspiratory curve ends in the right upper corner with this corresponding pressure representing the peak inspiratory pressure and the volume representing tidal volume. From this point the expiratory limb starts and it continues in the counter-clockwise direction and ends at the starting point [3].

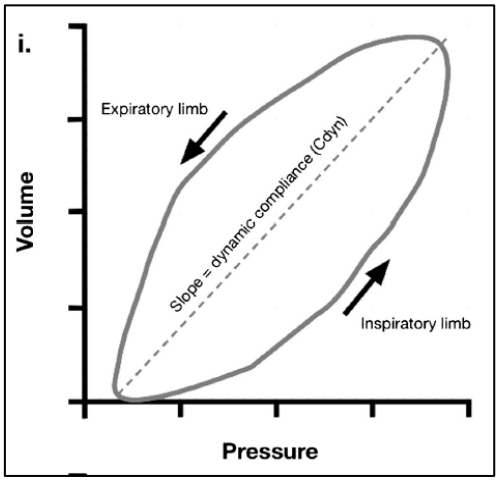

Figure 13: Pressure-volume curve demonstrating the inspiratory and expiratory limbs [8]

The inspiratory limb usually has a sigmoidal shape and this is related to changes in compliance. Initially there is a flat part which indicates the movement of air into the airways which are collapsed and so have a low compliance i.e. more pressure needs to be applied with minimal change in volume; this results in the curve bowing out to the right. The steep part of the curve indicates lung recruitment and an increase in pulmonary compliance. The curve flattens out again at the top indicating the end of inspiration and decreased compliance as alveoli become full and then overdistended [3, 8].

The shape of the graph also gives additional information to the clinician. Hysteresis describes how lung tissue does not act the same during inspiration and expiration and that for a given pressure there will be differing volumes in the lung during inspiration and expiration. The inspiratory and expiratory limbs of the graph have differing shapes and hysteresis represents the area in between the two limbs. Hysteresis is explained by the alveoli air-liquid surface forces and the opening and closing of alveoli [3]. With widening of the curve and “bowing” out of both the inspiratory and expiratory limbs there is an increase in airflow resistance due to either airway or circuit resistance or both.

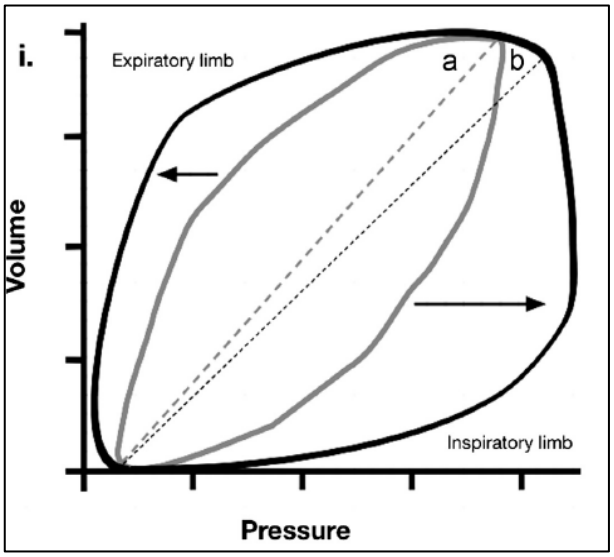

Figure 14: Pressure volume curve demonstrating “bowing” out due to increased airway resistance [8]

If a line is drawn to connect the starting inspiratory point and end inspiratory point, this will represent the pressure required to inflate the lung to the end inspiratory volume. This line does not represent airway resistances but the bowing out of the inspiratory limb away from this line represents the additional pressure required to overcome airway and tube resistances. The slope of this line also represents dynamic compliance. Changes in the compliance can change the shape of the curve with the line of dynamic compliance (C_{dyn}) being less steep and the curve lying closer to the x-axis representing decreased compliance. Increased compliance will cause a steeper slope of the graph with the graph lying closer to the y- axis [1, 3, 8].

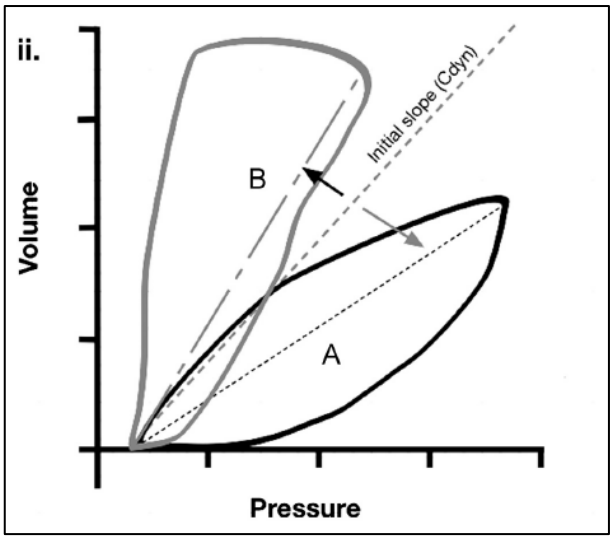

Figure 15: Pressure volume curve demonstrating changes in compliance. Curve A represents decreased compliance. Curve B represents increased compliance [8].

Two points can be noted on the inspiratory curve of maximal curvature known as inflection points. The lower inflection point (LIP) represents the point at which pulmonary compliance increases significantly due to the opening of collapsed alveolar units. The upper inflection point (UIP) occurs at the end of inspiration when there is a sudden decline in compliance as increasing pressure leads to minimal change in volume. If there is overdistension of the lungs the curve will take on an appearance of “beaking” [3].

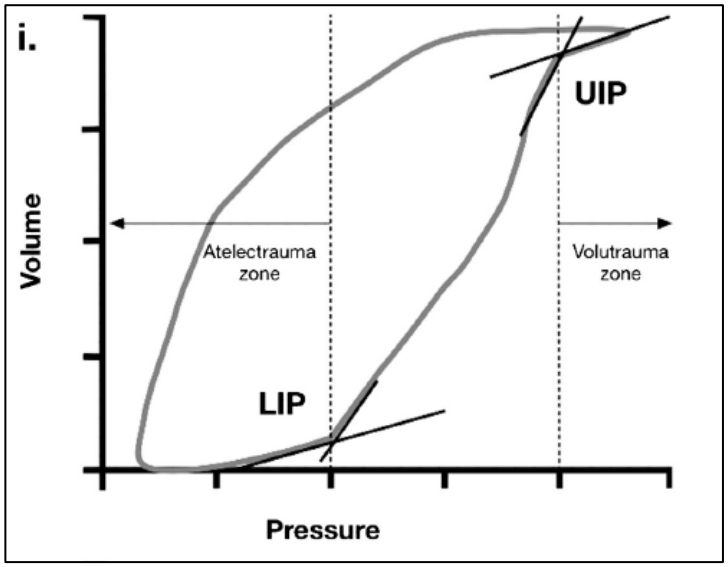

Figure 16: Pressure volume curve demonstrating the lower inflection point (LIP), upper inflection point (UIP) and “beaking” [8]

Atelectrauma occurs when there is constant opening and collapsing of alveolar units and this can be minimized by increasing the PEEP to the level of the lower inflection point or above this pressure. Volutrauma can occur with overdistension and this generally is seen when the curve takes on a beaked appearance as alveolar become overdistended. Lung protective ventilation strategies have recommended that the PEEP is kept at or above the level of the lower inflection point to avoid atelectrauma and that the peak inspiratory pressure is kept below the level of the upper inflection point to avoid volutrauma [3, 8].

Despite initial enthusiasm for using pressure volume loops to guide ventilation they require a well sedated or paralysed patient to be accurate. There is a move away from keeping patients deeply sedated or paralysed for any length of time as those management interventions have been linked to worsening ICU delirium and the development of critical illness neuromyopathy. The evidence regarding the use of pressure volume curves to guide lung protective ventilation are conflicting. Some studies have revealed that it is beneficial and will decrease the time on the ventilator as well as a reduction in mortality. Yet other studies have revealed that the PEEP used by the guidance of the lower inflection point is actually higher than what is actually needed for lung protective ventilation [1].

Leaks in the circuit can also be detected on pressure-volume loops with a missing volume as shown by an incomplete loop that is open.

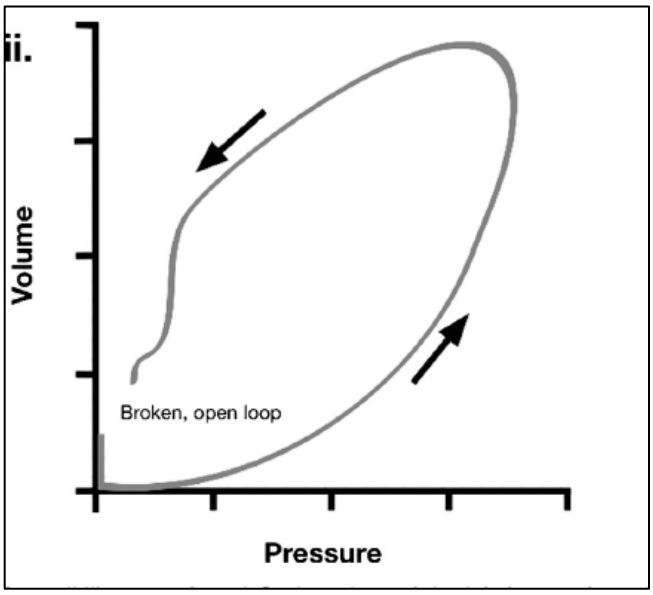

Figure 17: Pressure volume curve demonstrating a circuit leak with a "missing volume" and incomplete loop [8].

Patient effort can also be depicted on pressure-volume curves. This seen as a clockwise deflection prior to initiation of the breath and indicates the patient's work of breathing. The size of this "patient loop" indicates the work of breathing of the patient with a larger area equating to larger work of breathing. If the trigger is altered then it can be seen visually if the patient is required to perform more or less work to trigger the breath [8].

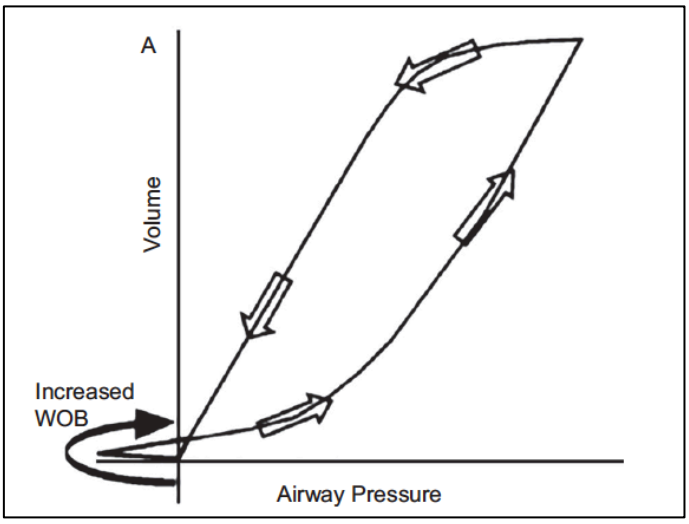

Figure 18: Pressure volume curve demonstrating patient respiratory effort and their work of breathing [1].

Work of breathing is useful in assessing patient efforts and guiding the process of weaning from the ventilator. It also allows ventilation to be optimised to assist the patient when they start spontaneous efforts. Use of the work of breathing can complement the rapid shallow breathing index (RSBI = RR (bpm) / V_T (Litres)) to assist with weaning success predictions. It has been proposed that this indirect measure of work of breathing may be inaccurate and that more direct measures should be used such as oesophageal pressure (P_{es}) monitoring which measures intra-pleural pressures more accurately. At this stage no study has demonstrated which method best measures patient effort and accurately predicts weaning success by allowing ventilation modifications to support [1].

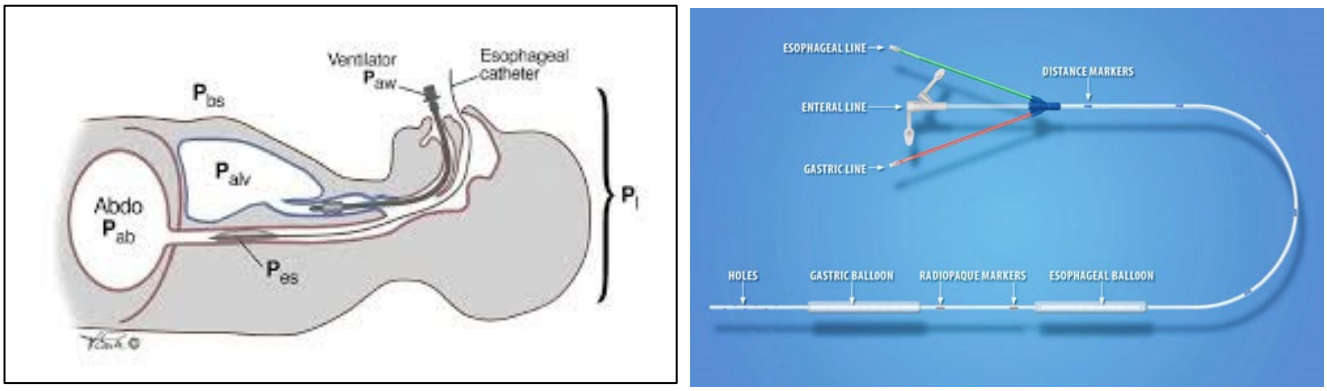

Figure 19: Depictions of oesophageal pressure monitors and their position once placed.

The pressure volume curves also have different shapes depending on the mode of ventilation used. Below are two diagrams showing the different shapes with differing end points (set tidal volume versus set peak inspiratory pressure) and how changes in compliance are illustrated [2].

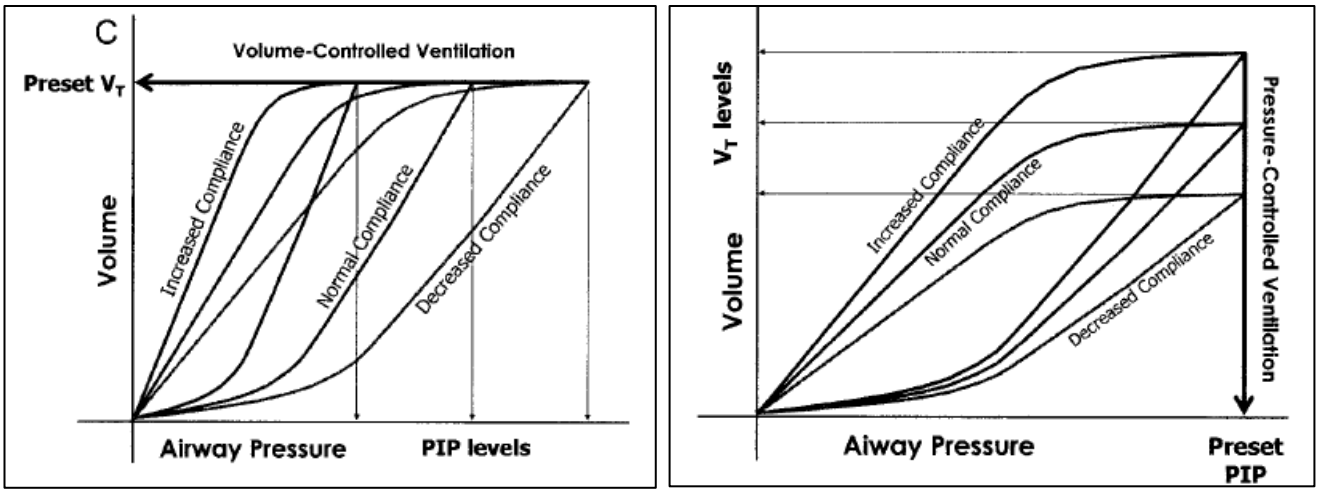

Figure 20: Pressure volume curves showing the difference in their shapes with volume controlled ventilation (left image) and pressure controlled ventilation (right image)[2]

(ii) Flow Volume Loop

This loop is traditionally part of the lung function test with expiration illustrated above the x-axis and inspiration below the x-axis. On ventilators the orientation of this loop is flipped over. Volume is on the x-axis and flow on the y-axis but the inspiratory loop occurs above the x-axis and expiratory loop below the x-axis. This loop is able to provide information on peak inspiratory flow, peak expiratory flow and tidal volumes. Changes in their waveform can demonstrate air leaks and airway obstruction [1].

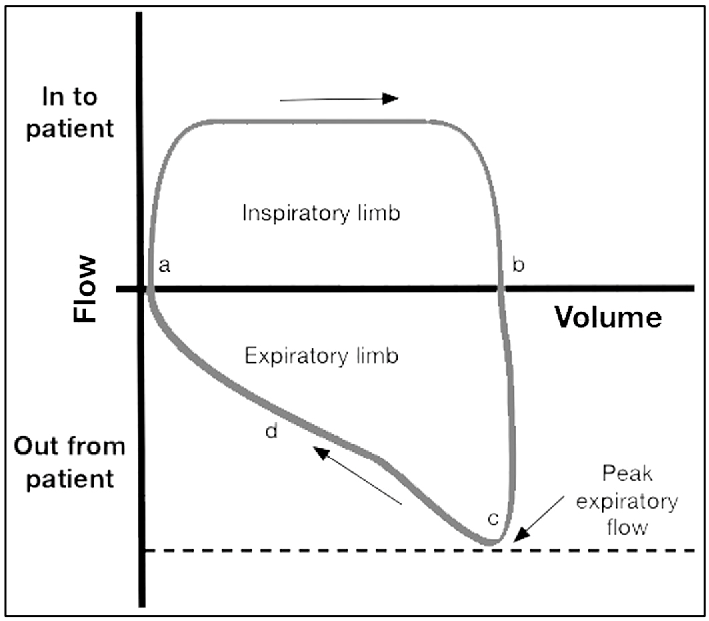

Figure 21: Flow volume loop [8]

The inspiratory loop starts at the interception of the x- and y-axes and travels in a clockwise direction. Initially both volume and flow increase but then flow starts to plateau and the curve decreases on the y-axis until it reaches zero flow. Once inspiration is complete the curve then crosses the x-axis and continues with the expiratory loop. This continues in a clockwise direction with a decreasing volume. Expiration is complete when the loop reaches zero volume and flow. The lowest point reflects the peak expiratory flow rate [3].

The shape of the inspiratory limb is dependent on the mode of ventilation. In pressure controlled modes the inspiratory limb has a descending shape, similar to the shape of the flow time scalar. With volume controlled modes or constant flow modes, the inspiratory limb is square shaped. Again similar to the flow time scalar [8].

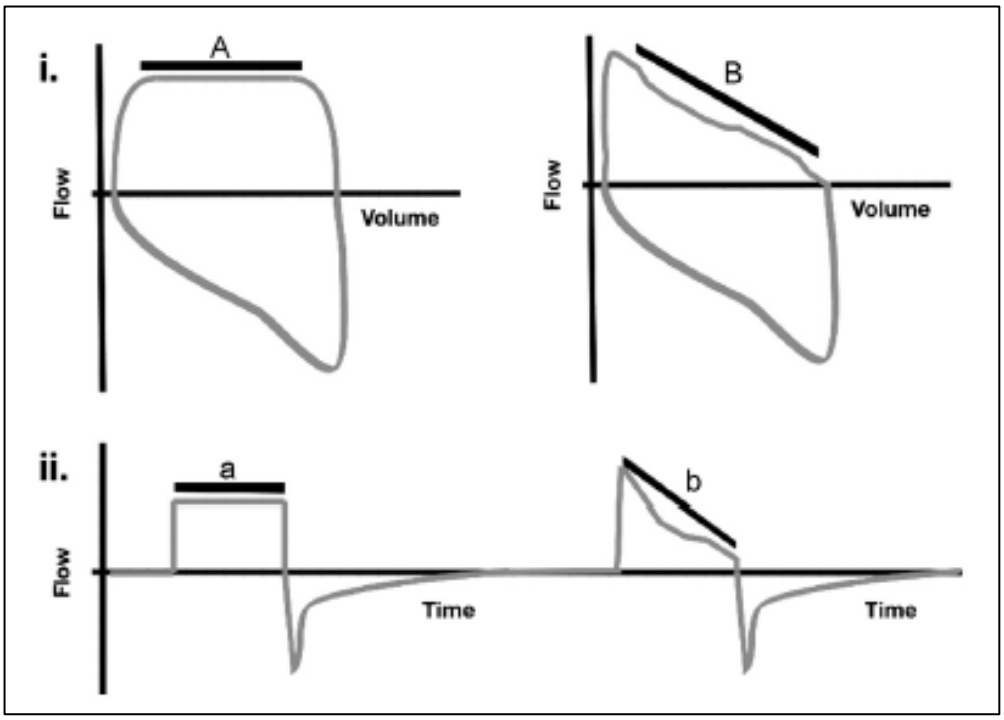

Figure 22: Flow volume loops demonstrated with volume controlled mode on the left and pressure controlled mode on right [8].

Important information can be obtained from the flow-volume loop with specific reference to the expiratory limb. If the expiratory limb has a “scooped out” appearance there is an increase in airway resistance, generally representing bronchospasm. This “scooped out” appearance is visible in the middle part of the expiratory limb, and there is also a corresponding decrease in the peak expiratory flow. This translates to lower flow rates at a given volume which is expected to occur in the presence or airway obstruction [3]. The flow volume curve can be used to assess response to treatment as well, and monitor changes to airway resistance [8].

The expiratory limb can also demonstrate air trapping with the curve not returning to zero flow prior to the next inspiration. It can also demonstrate air leaks where there is a missing volume shown by discrepancies between the volume on the inspiratory and expiratory limbs, but also a sudden drop of the flow to zero but not the volume [3, 8]. Airway secretions can also alter the expiratory limb and are visible as reverberations on the expiratory limb.

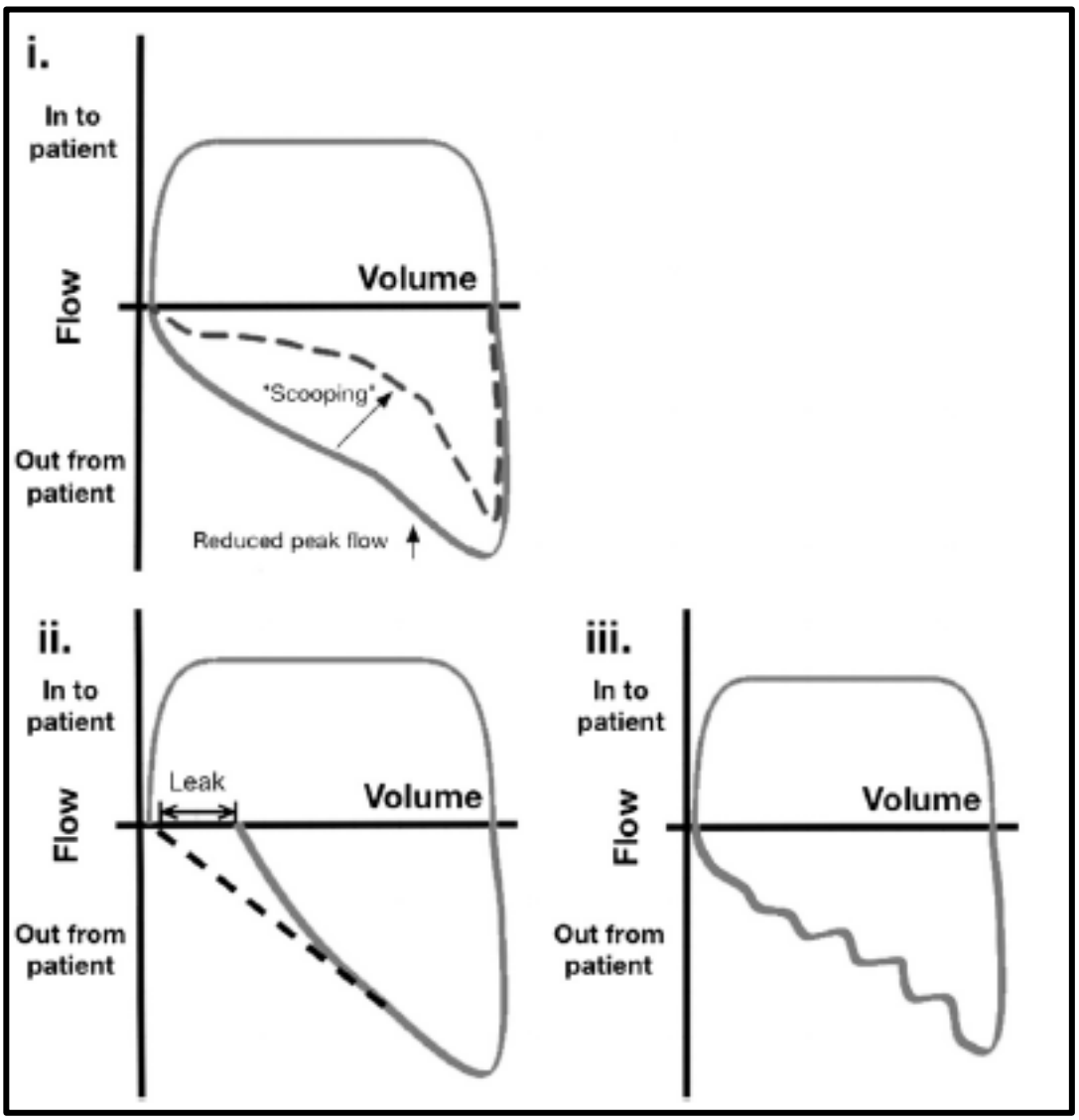

Figure 23: Flow volume loops demonstrating i) Scooped out appearance and decreased peak flow with airway obstruction. ii) a leak in the circuit with a "missing volume", iii) Airway secretions causing reverberations in the expiratory limb [8]

VENTILATOR MODE BASICS

(i) Terminology

Four variables determine how ventilators deliver mechanical breaths [3]:

1) Trigger
   This is the signal that initiates the mechanical breath. The breath can be initiated by the ventilator, which is called a controlled or mandatory breath, or by the patient which is a called a supported or an assisted breath. The patient may trigger a breath by generating a negative inspiratory pressure or negative inspiratory flow. The advantage of a flow trigger is that it is more sensitive to patient effort and therefore results in a low latency between triggering a breath and the ventilator delivering the breath. This however will result in false triggering if the trigger threshold is set too low (see later: ventilator dys-synchrony).

2) Target variable
   This is also referred to as the Control or Limit. After initiation of the breath, the breath is delivered in a set pattern during the inspiration period until the target is achieved. There are 2 types of target variables: a volume target (volume control) and pressure target (pressure control).

3) Cycle variable
   This is the signal that terminates the delivery of the breath. The cycle signal can be when a set volume has been delivered, a certain time has elapsed or there is a decrease in the flow from the patient. Mandatory breaths are time cycled while spontaneous breaths are flow cycled.

4) Baseline
   The baseline is the pressure that the airway and circuit returns to after the inspiratory phase cycles to expiration. It has been demonstrated that some degree of positive end-expiratory (PEEP) is beneficial for many physiological reasons and that zero end-expiratory pressure (ZEEP) should be avoided in many clinical scenarios.

(ii) Ventilatory breath sequences

The ventilator can deliver many different types of breath sequences depending on the effort and needs of the patient.
In controlled modes patients generally require sedation and often paralysis to prevent patient respiratory efforts from interfering with the ventilator. These modes require no patient work. Prolonged time spent ventilated by controlled modes leads to ventilator induced diaphragmatic dysfunction, with diaphragmatic atrophy. The controlled modes control all aspects of the respiratory cycle from the respiratory rate, to inspiratory time and tidal volumes [9].

Assist modes require the patient to make some form of respiratory effort and the work of breathing is shared between the patient and the ventilator. Assisted modes allow the patient to be less sedated and do not require paralysis. They prevent the same extent of diaphragmatic atrophy and allow patients to regain muscle function quicker. The amount of work done by the patient is variable and depends on the ventilator settings. Ventilator settings need to be adjusted to prevent patient-ventilator dys-synchrony, but this topic will be dealt with later [9].

There are 3 basic breath sequences worth noting as they are commonly used:

1. Continuous Mandatory Ventilation (CMV)
   This mode has the advantage of delivering a set minute ventilation or minute volume (MV = RR x V_T) irrespective of patient effort. The sequence is best used in scenarios of no patient effort e.g. patients paralysed under general anaesthesia. The trigger is time based and determined by the respiratory rate e.g. if the RR is set to 12bpm, a breath will be delivered every 5-seconds. The cycle is also time base and determined by the inspiratory time. The inspiratory time is calculated from the RR and the I:E ratio such that, if the RR is 10bpm each breath will be 6-seconds long and if the I:E ratio is 1:2 then the T_{insp} will be 2 seconds and hence the breath delivered will cycle to expiration after 2-seconds.
   The target variable can either be pressure or volume, therefore this breath sequence can result in 2 common ventilator modes:

   - Pressure control - Continuous Mandatory Ventilation (PC-CMV)
   - Volume control - Continuous Mandatory Ventilation (VC-CMV) [10, 11]

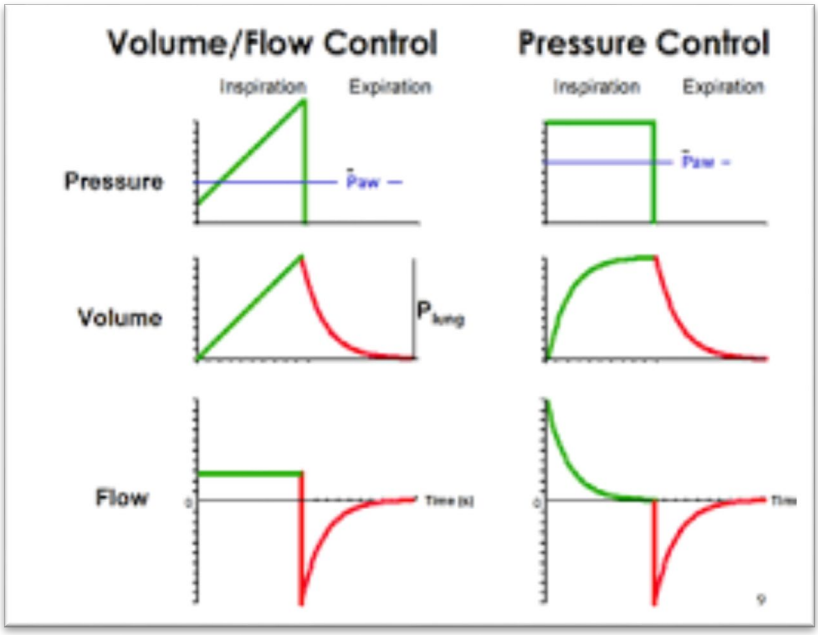

Figure 24: Different ventilator scalar shapes depending on mode of ventilation

2. Intermittent Mandatory Ventilation (IMV)
   This sequence allows a mix of both mandatory and spontaneous breaths. This sequence in modern ventilators works with synchronisation of the trigger and is referred to as synchronised Intermittent Mandatory Ventilation (SIMV). A mandatory respiratory rate is set by the operator which sets the minimum number of breaths. A “trigger window” exists for each breath. If the patient triggers a breath, a mandatory breath is delivered and is synchronised to the patient effort. If the patient triggers another breath before the next trigger window, the patient will receive a pressure support breath (this is a spontaneous breath). Should the patient not trigger a breath in the “trigger window”, the ventilator delivers a mandatory breath. If the patient has a RR greater than the set RR, the patient will received the set number of mandatory breaths and any breaths over and above this will be pressure supported spontaneous breaths.

The target variable can either be pressure or volume, therefore this breath sequence can result in 2 common ventilator modes:

- Pressure controlled Synchronised Intermittent Mandatory Ventilation (PC-SIMV)
- Volume controlled Synchronised Intermittent Mandatory Ventilation (VC-SIMV) [10, 11]

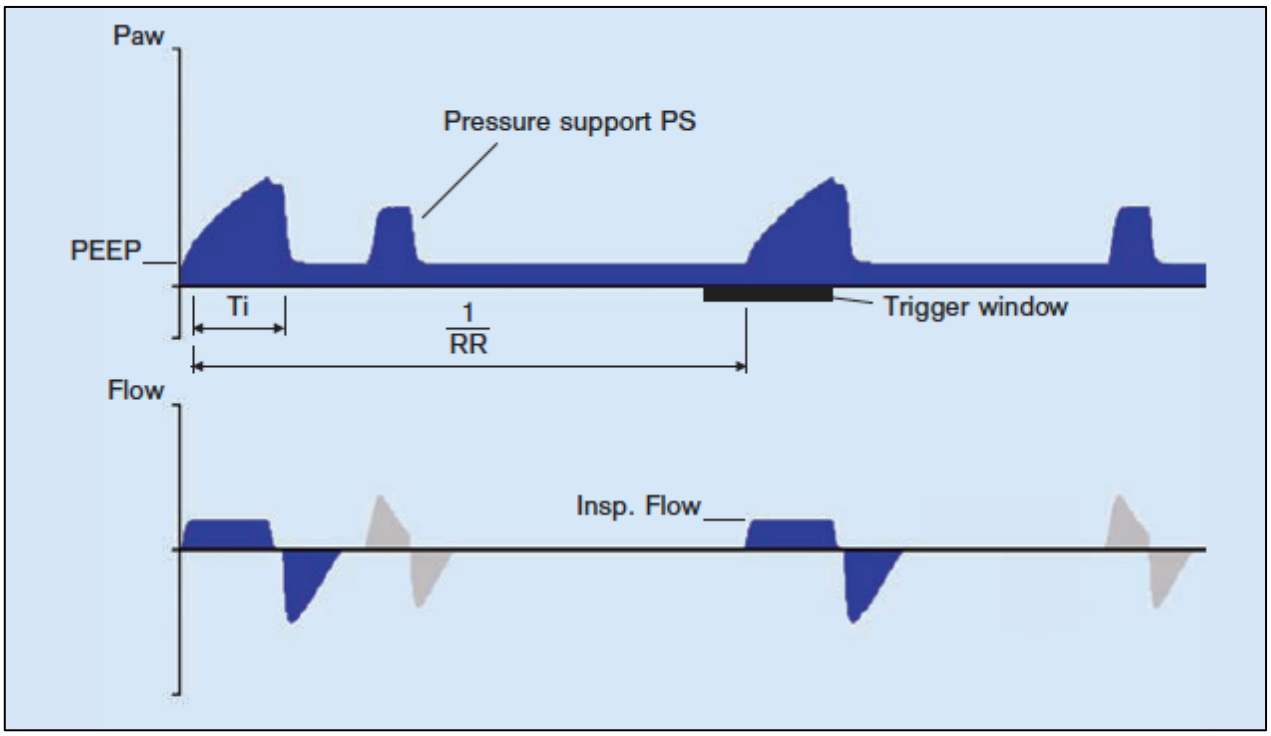

Figure 25: Volume controlled-SIMV (VC-SIMV) [11]

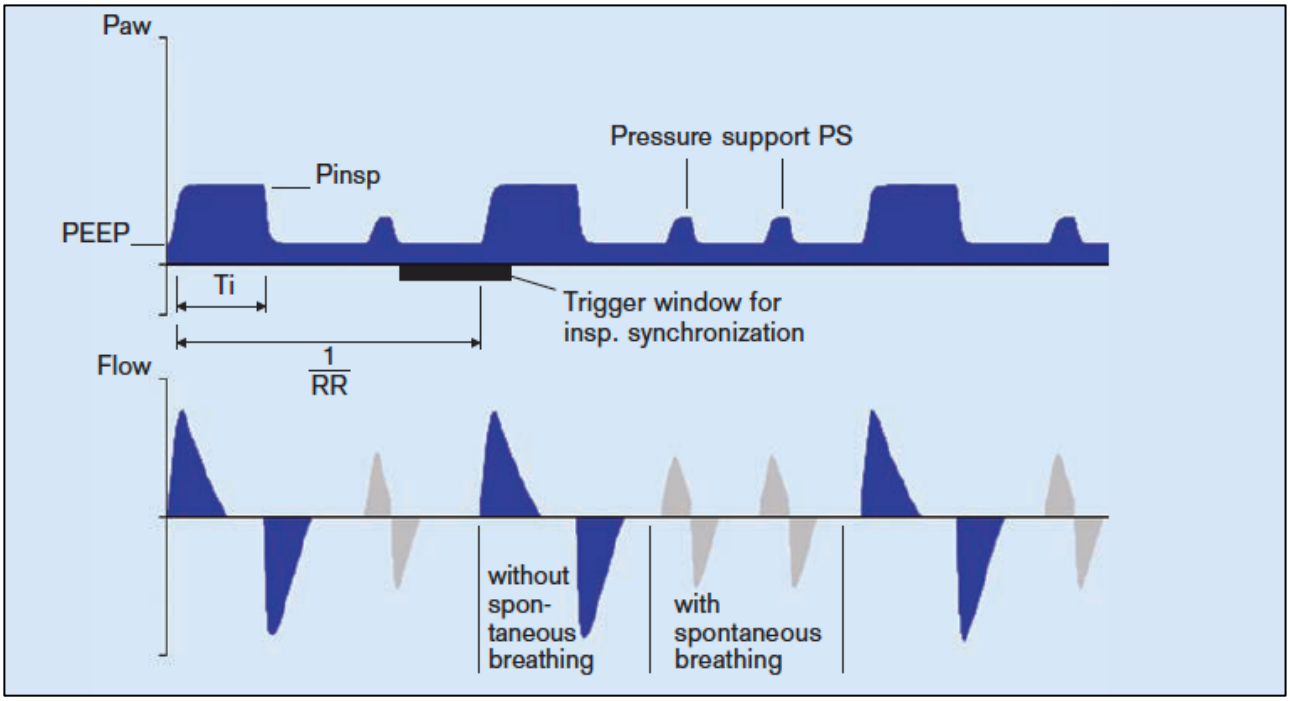

Figure 26: Pressure control- SIMV (PC-SIMV) [11]

3. Continuous Spontaneous Ventilation (CSV)
   This mode has no mandatory ventilatory breaths. The patient must trigger every breath according the patient's respiratory drive. These spontaneous breaths maybe supported with pressure support. The patient also controls the cycling of the pressure support from inspiration to expiration. The cycle is usually a flow cycle where the ventilator terminates the inspiratory pressure support once the flow rate drops to 30% of the initial flow rate. Since this sequence most commonly only used pressure support, only one mode is commonly used:

   - Spontaneous- CPAP with pressure support (SPN-CPAP/PS)[10, 11]

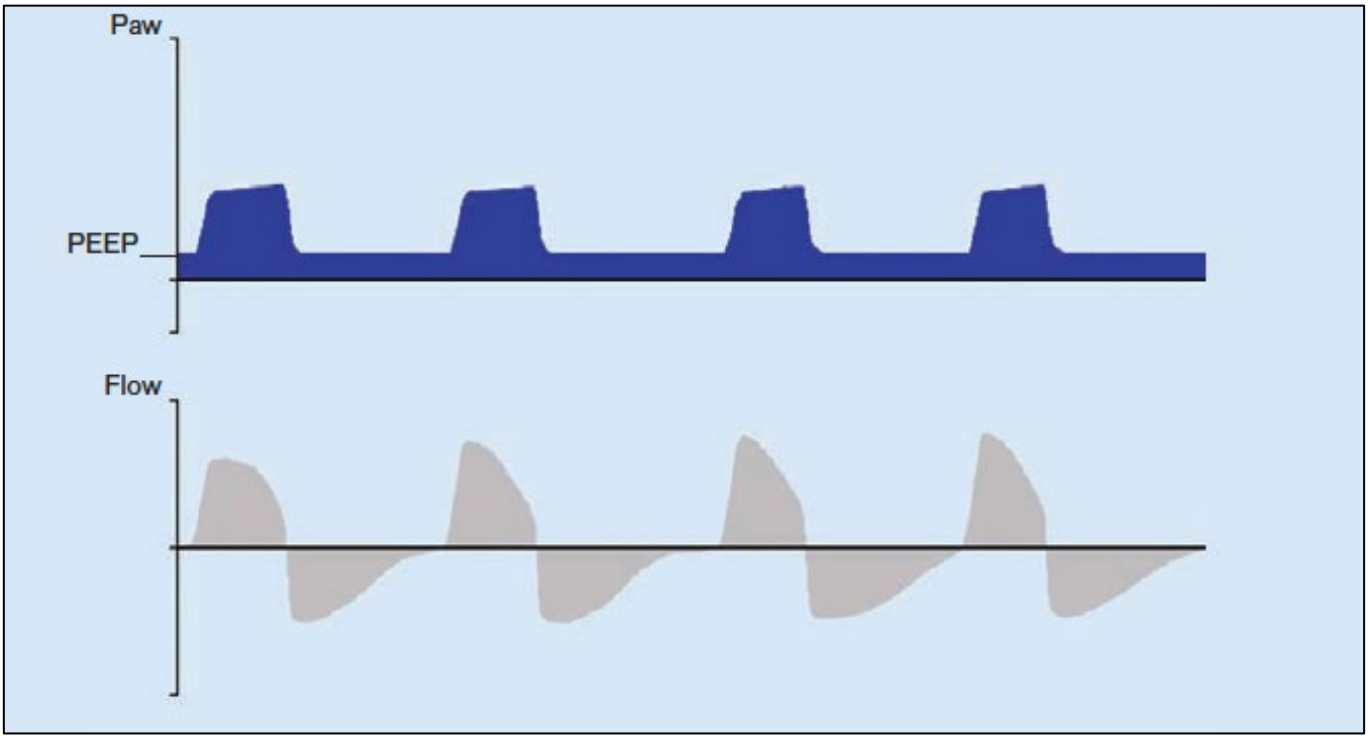

Figure 27: Spontaneous- CPAP with Pressure support (SPN-CPAP/PS) [11]

VENTILATOR PATIENT DYS-SYNCHRONY

Mechanical ventilation is the most common life support procedure performed in ICUs. It is life-saving and is instituted to decrease the work of breathing, improve patient comfort, improve oxygenation and gaseous exchange and to allow time to treat the cause of respiratory failure. However, mechanical ventilation is not without complications. These are ventilator associated pneumonia, ventilator associated lung injury, and ventilator induced diaphragmatic dysfunction, amongst others. In order to prevent diaphragmatic dysfunction, clinicians make use of assist and support ventilatory modes. These modes require patient effort and therefore the interaction between patient effort and the ventilator needs to be harmonious [12].

Patients that are mechanically ventilated can make no respiratory effort and the ventilator controls their breathing. Otherwise patients can make some respiratory effort and then ventilation is controlled by both the ventilator and the patient. Therefore the patient-ventilator interaction is vitally important. Clinicians need to have an understanding of the different forms of patient ventilator dys-synchrony and be able to identify them and manage them [13].

Kondili *et* al. gave an insightful definition into patient ventilator dys-synchrony:
"During mechanical ventilation the respiratory system is affected by 2 pumps: the ventilator controlled by the physician and the patient's own respiratory muscle pump. Patient-ventilator interaction is an expression of these 2 controllers, which should be in harmony if the result is to be appropriate for the patient" [14]. This mismatch occurs not only between the ventilator and the patient's respiratory muscles, but also involves the patients diaphragm, nervous system and respiratory centres [15].

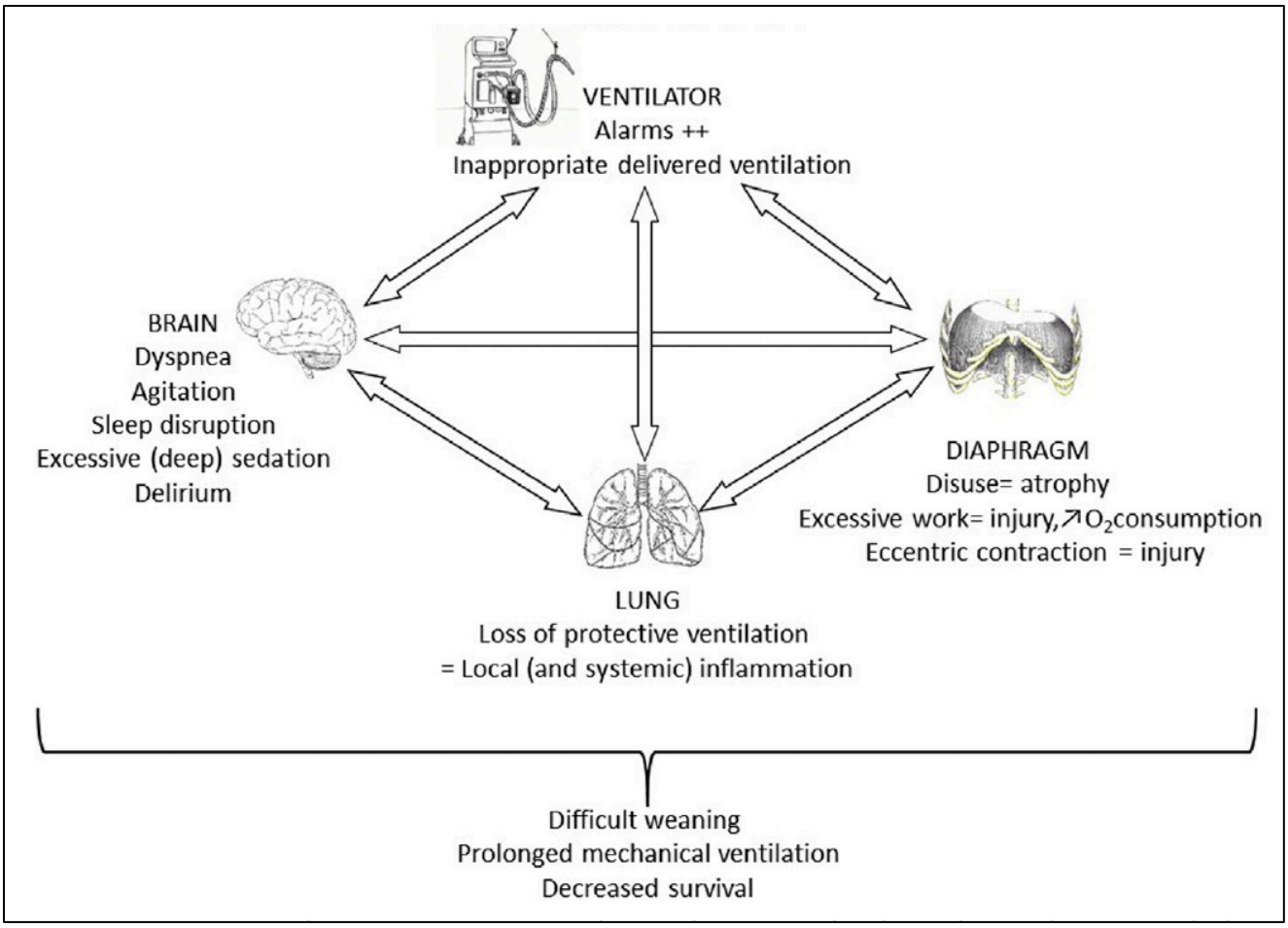

Figure 28: Demonstration of the interaction between the different organs and ventilator during dys-synchrony [15].

The patient's pump is controlled by the neuromuscular system, mechanical and chemical factors. The ventilator pump is controlled by the clinician and the settings of the ventilator. For there to be complete synchrony between the patient and the ventilator there needs to be matching of every phase of the breath. Dys-synchrony can occur during any of the phases of the breath cycle i.e. during: Triggering, delivery of the breath or inspiration and, cycling or expiration (Table 1) [14]. Dys-synchrony is a common phenomenon occurring roughly in one third of ICU ventilated patients and it leads to patient discomfort, increased work of breathing, delayed weaning and prolonged ventilation; which all contribute to poorer outcomes [15].

Table 1. Factors That Affect Patient-Ventilator Synchrony

Ventilator Factors
Trigger variables: esophageal pressure, flow, or shape signal
Sensitivity setting
Rise-time capability
Design, mode, and settings of the flow delivery system
Flow pattern selected
Design of the exhalation valve
How positive end-expiratory pressure is generated by the software
Extraneous flow (eg, from a nebulizer or added oxygen)
Patient Factors
Sedation level: pain, splinting
Inspiratory effort/respiratory drive; neural timing
Pathology of the respiratory system or abdomen; secretions
Intrinsic positive end-expiratory pressure
Size and type of airway
Presence of leaks

Monitoring Techniques for Asynchrony or Dys-synchrony

Clinical monitoring of ventilated patients remains most important. Patients vital signs should be assessed and patients should be examined for signs of respiratory distress and discomfort. These may be difficult to detect; however, patient discomfort can be displayed as dyspnoea, anxiety, diaphoresis or nasal flaring. Patient's metabolic status should be checked and regular arterial blood gases performed. It is also important to ensure other causes of discomfort are excluded, such as pain [9].

Ventilator graphics can be used as a non-invasive measure to detect signs of dys-synchrony and can assist in optimizing ventilator settings to improve patient-ventilator synchrony.

Interpretation of these graphics requires skill as there is no automated analysis from ventilators regarding the waveforms. Clinicians should be encouraged to undergo training in the interpretation of ventilator waveforms as they are easily available at the bedside.

Other modalities of detecting dys-synchronies include electrical activity of the diaphragm and oesophageal pressure monitoring but these methods are beyond the scope of this review.

Classification of Patient-ventilator Dys-synchronies

(i) Dys-synchronies related to triggering

When the patient makes a spontaneous effort they increase their intra-thoracic volume and this leads to a decrease in airway pressure and an increase in airflow. The ventilator can be set to pressure-triggering or flow-triggering and when the patients effort reaches the trigger threshold set by the ventilator then the breath is supported. There is usually a time delay between the patients effort and the ventilators support response that can be seen on the ventilator graphics (trigger latency). The pressure scalar will show a transient decrease in pressure and the flow scalar will show an increase in flow [16].

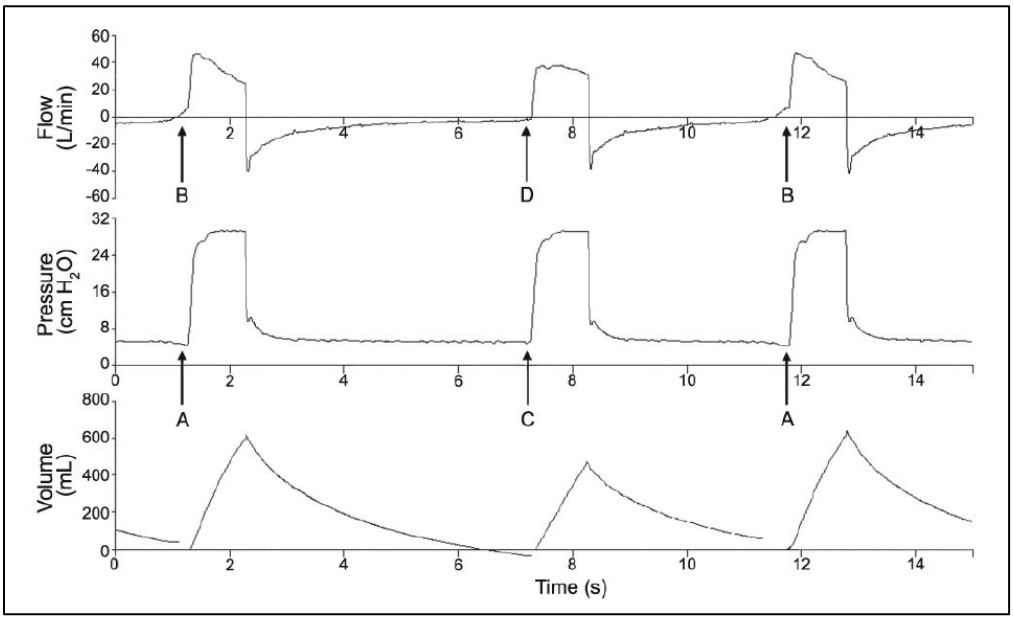

Figure 29: Patient-ventilator interactions. The first and third breath are triggered by the patient, they demonstrate a pressure decrease (A), and an increase in flow (B) prior to the assisted breath. The second breath is machine triggered and demonstrates no decrease in pressure (C) or increase in flow (D).[16]

(a) Ineffective triggering: The patient initiates a breath and the ventilator fails to recognise it appropriately and either fails to support the patient effort at all or is delayed in the support.

This could be due to an inappropriately set trigger threshold or the presence of intrinsic PEEP that makes it harder for the patient to trigger ventilatory support. Intrinsic PEEP is an additional pressure that the patient has to overcome before the ventilator recognizes the patients spontaneous attempt [3]. Ineffective triggers are only detected by visualisation of the ventilator graphics as they are not added to the ventilators respiratory rate [16].

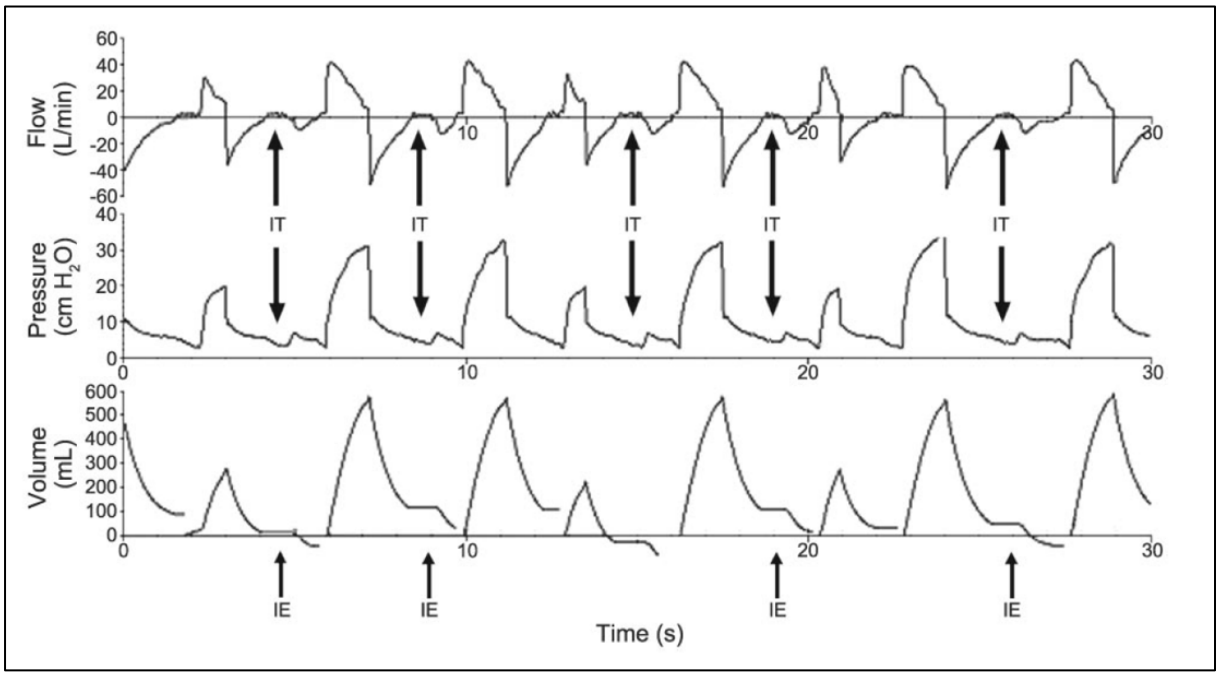

Figure 30: Scalar waveforms for volume controlled ventilation showing ineffective triggers (IT)[16]

(b) Double triggering: This occurs when the patients inspiratory effort is longer than the ventilators set inspiratory time and even continues after the ventilatory inspiratory time is complete, therefore immediately triggering a second inspiration. This results in the patient receiving a double tidal volume prior to exhalation. This could be due to the patient having a very high respiratory drive or inappropriate ventilatory settings such as too low tidal volume and too short inspiratory time [16]. Double triggering can lead to breath stacking, with subsequent breaths occurring without adequate expiratory time and is related to shorter cycling [15].

(c) Auto-triggering: This occurs when the ventilator delivers an assisted breath without patient effort initiating it. This is mostly caused by circuit leaks or cardiac oscillations and requires an adjustment to the trigger sensitivity as the trigger sensitivity is too low [12].

(d) Reverse triggering: This can look similar to double triggering. This occurs when a ventilator triggered breath leads to the contraction of the diaphragm which is then detected by the ventilator as a patient effort and it will trigger a second breath. This is seen to occur in heavily sedated patients [3, 12].

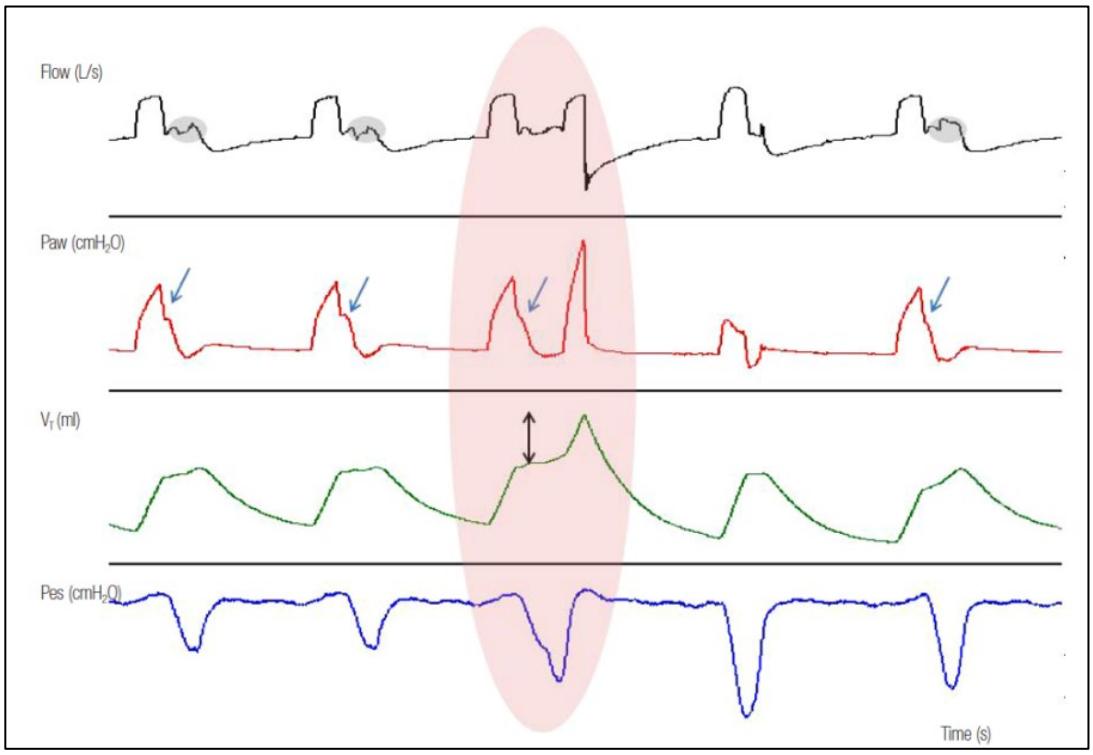

Figure 31: Reverse triggering in assist volume control ventilation. The oesophageal pressure tracing shows patient respiratory effort after each mechanical breath. In the red shaded area a reverse triggered breath was strong enough to trigger the ventilator at the end of the mechanical breath. This results in breath stacking and a 'double tidal volume' [17]

(ii) Dys-synchronies related to Flow

Flow starvation: This occurs when the ventilator gas delivery does not meet the high respiratory demands of the patient. This is seen on the pressure curve with a concave indentation as if the patient is trying to suck in more air with a negative indentation [15]

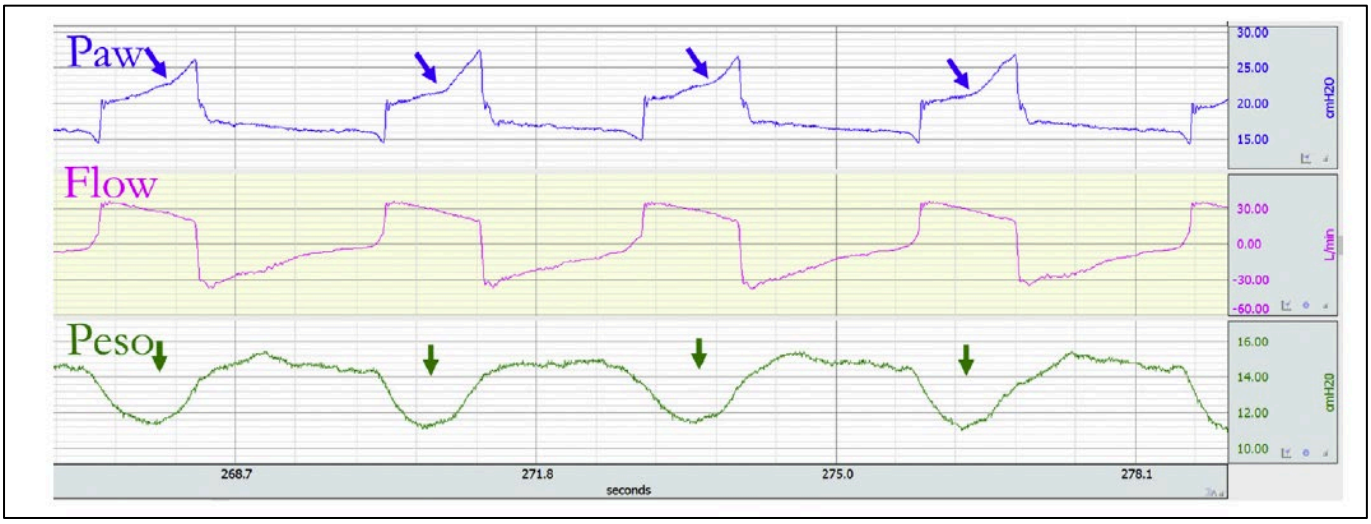

Figure 32: This waveform tracing demonstrates flow starvation. During inspiration there is a concave deflection in the pressure scalar and a negative deflection in the Oesophageal pressure tracing indicating patient effort[15].

(iii) Dys-synchronies related to Cycling

(a) Premature cycling: The mechanical inspiratory time is too short for the patients desired inspiratory time and so the patients inspiratory effort continues into the mechanical expiration time [15]. This can also lead to double triggering. A patient with a high respiratory drive and ventilator settings with a low tidal volume and short inspiratory time will be at risk for double triggering.

(b) Delayed cycling: This is the opposite of premature cycling. The ventilator's inspiratory time is too prolonged and there is either no effort from the patient at the end of the inspiratory cycle or the patient is actively trying to exhale during the ventilator-assisted inspiration.
Delayed cycling can lead to insufficient expiratory time and this can result in air-trapping.

Pressure support induced apnoeas

If patients are over-ventilated from too much ventilator assistance or mandatory breaths, a drop in their arterial CO_2 levels well result. This creates a form of patient-ventilator dys-synchrony that leads to central apnoeas. If there is inadequate ventilator backup during these central apnoeas, this will lead to sleep fragmentation. It is therefore very important to prevent excessive ventilatory assistance with pressure support modes, especially when patients are sleeping or sedated [12].

Consequences of patient-ventilator dys-synchronies

Dys-synchronies have significant effects on ventilated patients. Studies have demonstrated that dys-synchronies lead to increased duration of mechanical ventilation. Double triggering will lead to increased tidal volumes being delivered which can lead to dynamic hyperinflation and ventilator induced lung injury. Hyperventilation and hypocapnia can lead to sleep fragmentation and disturbances as well. They also lead to increased patient discomfort and anxiety. However, it is still undetermined if dys-synchronies lead to increased mortality or if they are just a marker of increased severity of illness [12].

Table 2. Deleterious Effects of Patient-Ventilator Asynchrony

Patient fights the ventilator
More sedation required
Higher work of breathing
Muscle damage
Ventilation-perfusion problems
Dynamic hyperinflation
Delayed or prolonged weaning
Longer stay
Higher costs

CONCLUSION

Ventilator graphics are non-invasive and easily available on every ventilator in both theatre and ICU. Interpretation of these graphics by clinicians at the bedside will result in insights into the patient's respiratory mechanics as well as the patient-ventilator interaction.

Detecting abnormalities on the graphics prior to detecting them clinically can allow for the expedited management and adjustment of ventilation settings to improve patient's respiratory function and optimise their ventilation.

Mechanical ventilation, although a life-saving intervention has significant complications. Every effort should be made to liberate the patient from the ventilator in a timeous manner and to wean them from controlled modes to assist/support modes as soon as possible. Interpretation of ventilator graphics can assist in optimising patients respiratory mechanics, improving patient ventilator interaction and ultimately weaning from the ventilator expeditiously.

However, interpretation of ventilator graphics requires skill and practice, and clinicians are encouraged to ensure they have a basic understanding of ventilator graphics to improve patient management and safety.

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